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1.   INTRODUCTION

Of the various hosts for diode pumped Nd lasers, $La_2Be_2O_5$ (BEL) offers several unique advantages. These include a relatively broad spectral absorption bandwidth and a crystal orientation which makes the rod athermal. In addition, the crystal growth and polishing technology of this material is relatively mature. Unlike some other hosts, the 810 nm absorption peak of Nd:BEL is close to the Nd:YAG absorption band, so that in many cases the same diode array pumps can be used for both BEL and YAG hosts.

The absorption spectra using unpolarized light for Nd:BEL and Nd:YAG are shown superimposed in Figure 1. It can be seen that in BEL not only is the Nd absorption broader than in YAG but it is also more intense in the spectral region of 805 to 820 nm.

In this work we present a comparative study of laser diode pumped cw Nd:BEL and Nd:YAG. We show that both hosts perform well, and specify under what conditions BEL might be the better host.

2. EXPERIMENT

The outputs of two 500 mW phased arrays were collimated with an anamorphic lens pair and combined using a polarizing beamsplitter cube as shown schematically in Figure 2. The diodes are mounted on active heat sinks for wavelength control. The output spectrum of the laser diodes as measured with an OMA show 5 to 6 longitudinal modes operating simultaneously with a total bandwidth of about 1.5 nm. With both arrays operating at 500 mW, approximately 700 mW could be focussed onto one face of a 1 cm long Nd:host rod. This face had a dichroic coating that was a high reflector (HR) for 1.06μ and was specified greater than 85% transmissive at 808 nm. The focussed spot size
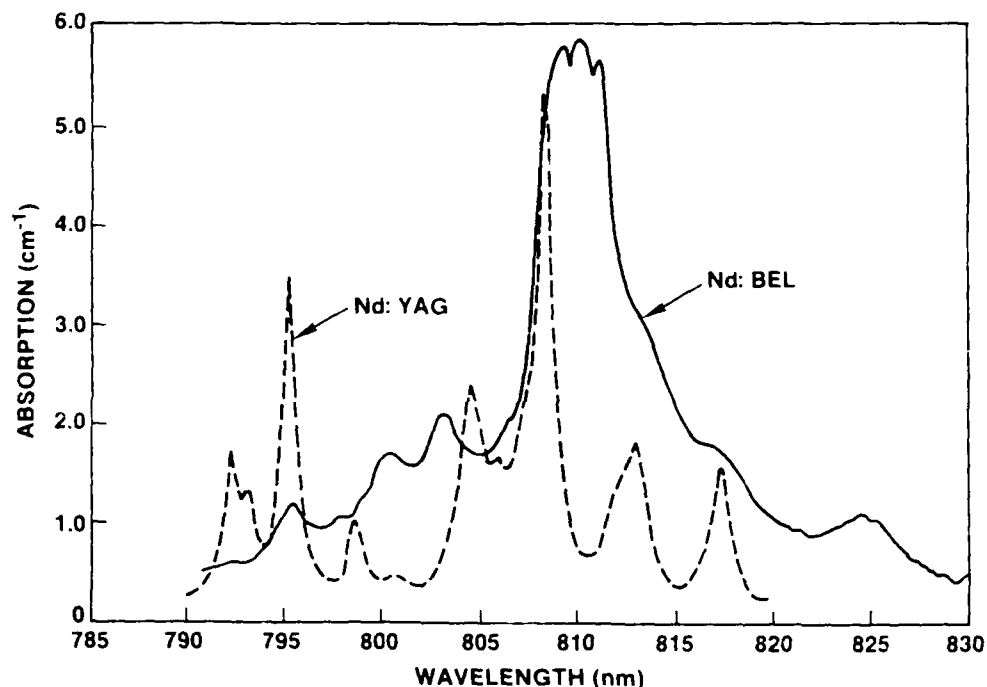

Figure 1. Absorption spectra of Nd:BEL and Nd:YAG.

consists of two unequal intensity lobes separated by 50μ; 99% of the pump energy was contained in a rectangular area 75μ wide by 10μ high. These are forty stripe arrays with an emitting length of 400μ. The resonator geometry was nearly hemispherical.

3. RESULTS

3.1 Power

The output power in the IR as a function of laser diode pump power is shown for both hosts in Figure 3. The comparison was performed using a 95% output coupler. It can be seen that both rods have a 42% slope efficiency, with BEL having a higher threshold. The dependence of the output power on the mirror reflectivity was measured for reflectivities between 95% and 99.9% and the results are shown in Figure 4. The flatness of the YAG curve contrasts

dramatically with the high degree of sensitivity shown by BEL to output reflectivity. A peak output of 250 mW was measured for BEL at 98% reflectivity while the peak for YAG was 283 mW at 97% reflectivity. The threshold pump power as a function of output coupling was also measured. At 98% the pump threshold for BEL was 92 mW, while at 97% the threshold for YAG was 61 mW. From the dependence of the threshold power on mirror reflectivity one can derive the single pass loss for BEL and YAG (.002 and .012, respectively) and the small signal gain dependence on pump power. For BEL this number was one-third that for YAG, which is approximately the same ratio as the stimulated emission cross sections for Nd in the two hosts.

3.2 Efficiency

From an empirical point of view one can factor the overall efficiency into the product of three measurable quantities, as shown in Table 1 for BEL and YAG. The first factor is the electrical to optical pump light conversion
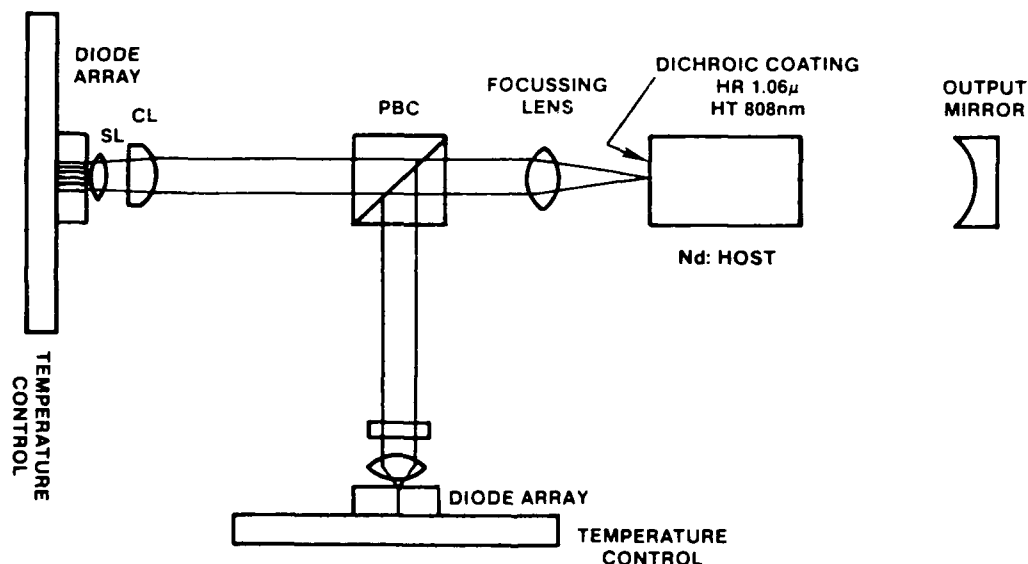

Figure 2. Nd end-pumped laser geometry.

efficiency for the laser diode. The efficiencies for the 500 mW arrays used in this work are a factor of 2 lower than presently available and this of course reduces the overall efficiency shown in the last column by the same factor. The lower efficiency for the diodes used to pump BEL reflects the higher junction temperature needed to wavelength tune to the (red-shifted) absorption peak. The power consumption of the coolers is not included in the overall efficiency. The collection efficiency of the optics is a function of the numerical aperture of the lenses and the reflectivity of the AR coating. The higher number for BEL is a result of using higher quality coatings. The third factor is the pump light to IR conversion efficiency of the laser rod, and is given for the optimum output coupling for each host. The lower number for BEL is due to the higher threshold.

Table 1. Measured efficiency factors for Nd:host lasers

Host	Electrical to 808/810 nm	Collection optics	808 nm to 1.06μ or 810 nm to 1.07μ @R	Overall efficiency (%)
YAG	.170	.63	.40 @ 97%	4.3
BEL	.135	.75	.35 @ 98%	3.5

The measured efficiencies can be better understood by considering in greater detail the processes affecting the overall efficiency for an end pumped Nd:YAG laser. An SAIC[1] report commissioned by NOSC provides a basis for this discussion, and these results are reproduced in Table 2 and compared with the measurements obtained in the present work.

Table 2. Efficiency factors for end-pumped Nd:YAG

Process	SAIC			This work		
Diode efficiency	0.24			0.17		
UPPER STATE EFFICIENCY (USE)						
Stokes efficiency	0.76	USE		0.76	USE	
Quantum efficiency	0.80	0.60		(0.80)	0.38	
Transfer efficiency	0.98		OPT CONV EFF	0.63		OPT CONV EFF
OUTPUT EFFICIENCY (OE)			0.36			0.23
Beamfill factor	0.90	OE		(0.9)	OE	
ASE losses	1.0	0.60		1.0	0.61	
Extraction efficiency	0.95			(0.95)		
Resonator losses	0.70			0.71		
Overall efficiency (%)	8.6			3.9		

Table 2 classifies the efficiency factors into three categories: the diode efficiency which is a measure of the conversion by the laser diode arrays of electrical power into pump radiation; the upper state efficiency which measures the transfer of the pump energy to the upper laser level; and the output efficiency which measures the conversion of the stored upper state energy into 1.06μ laser radiation. The diode efficiency used by SAIC was based on a McDonnell-Douglas report[2] and considered typical.

The upper state efficiency terms include the Stokes term which is the quantum defect between the pump photon energy and the laser photon energy, the quantum efficiency which is the fraction of absorbed photons leading to upper laser level population, and the transfer efficiency which measures the fraction of pump photons that are absorbed. The quantum efficiency was recently measured[3] and reported to lie within the range of 0.6 to 0.8. The upper end of this range was chosen for the purposes of this table (numbers in parenthesis in the table indicate quantities not measured in the present work). It is important to note that the product of the Stokes and quantum efficiencies is .61, which represents the maximum "theoretical" slope efficiency for Nd:YAG.

The transfer efficiency measures photon transport from the array to the rod and subsequent absorption by the Nd. It is therefore the product of two terms. We can write

$$P_A = P_D \eta_t \tag{1}$$

and

$$\eta_t = (1-\exp(-\alpha_D \ell))(1-r) \tag{2}$$

where P_A is the power absorbed by the rod, P_D is the power emitted by the laser diode array, η_t is the transfer efficiency, α_D is the absorption coefficient of the laser rod at the diode wavelength, ℓ is the path length of the pump radiation in the rod, and r summarizes the losses occurring between the pump array and the Nd:YAG rod (collection efficiency). Empirically it is observed that almost all of the pump radiation entering the rod is absorbed so that the transfer efficiency term will be determined by the collection efficiency. We have used the value of 0.63 from Table 1 for this number, although this does not take into account the reflection of pump radiation by the dichroic coating on the end pumped face of the rod. (This reflection loss was also assumed to be 0 in measuring the threshold power and in drawing the abscissa in Figure 2). The product of these three terms gives an upper state efficiency of 0.38 for this work.

The output efficiency is the product of four terms, although the amplified spontaneous emission (ASE) losses will be zero for a cw system. The extraction efficiency will also be high for this case as shown in the table. The beamfill factor is a measure of the spatial overlap of the resonator mode with the inversion profile created by the pump beam. Clearly for the end pumped configuration this number should be high but not 1.0 since the pump geometry used in this work does not match the resonator mode. Instead a short focal length lens is used to concentrate the pump energy into a small volume which absorbs most of the pump light in the region of spatial overlap.

The resonator loss term can be determined from the single pass loss and output mirror reflectivity using the expression

$$\eta_r = (1+L/(1-R))^{-1} \tag{3}$$

where η_r is the efficiency term due to resonator losses, L is the single pass optical loss due to scattering, absorption and reflection, and R is the

reflectivity of the output mirror. The SAIC results are based on a system presented in reference 2; in this work we use the .012 single pass loss determined in the threshold measurements mentioned above to obtain .71 for η_R with R=.97. The product of these four efficiency factors gives an output efficiency of 0.61.

The product of the upper state efficiency and the output efficiency gives the optical conversion efficiency which for this work is 0.23. Since the optical conversion efficiency takes into account all efficiency factors except the diode efficiency, this number can be compared with the measured value of 0.25 (the product of the third and fourth columns of Table 1 for Nd:YAG). This agreement is quite satisfying and gives at least circumstantial credence to the estimated values shown in parenthesis in Table 2. The overall efficiency shown in Table 2 is the product of the optical conversion efficiency and the diode efficiency and therefore the calculated value will be close to the measured efficiency of Table 1.
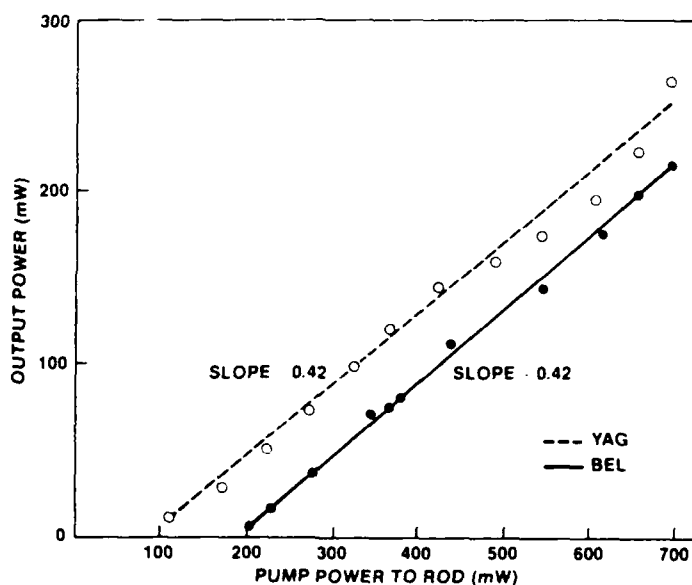

Figure 3. Laser output power dependence on pump power.

Using an intracavity lens and a KTP crystal we obtained several milliwatts of green light from both YAG and BEL. The conversion efficiencies were extremely low due to reflection losses by the lens coating and alinement sensitivity of the resonator. As a result of the poor conversion efficiency, longitudinal mode coupling[4] was not observed and good amplitude stability of the second harmonic output was obtained.

4. CONCLUSIONS

Under the conditions used in the present work, both BEL and YAG perform comparably well. The broader absorption bandwidth in BEL did not appear to enhance its performance, but this might be expected in an end pumping configuration where the absorption pathlength is long and the spectral

bandwidth of the laser diode arrays is relatively narrow. The lower stimulated emission coefficient and shorter fluorescence lifetime in BEL contribute to the higher lasing threshold and greater sensitivity to cavity losses (including output coupling). At higher pump power however the efficiency of BEL will improve relative to YAG. In addition, for side pumping or for pumping with broader spectral bandwidth arrays, the broader absorption in BEL will become a factor. It is also important to recognize that a minimum of 24% (corresponding to the quantum defect) and perhaps greater than 40% (if the quantum efficiency also contributes) of the pump radiation is converted to heat so that at high pump fluence athermal BEL might prove a superior host.
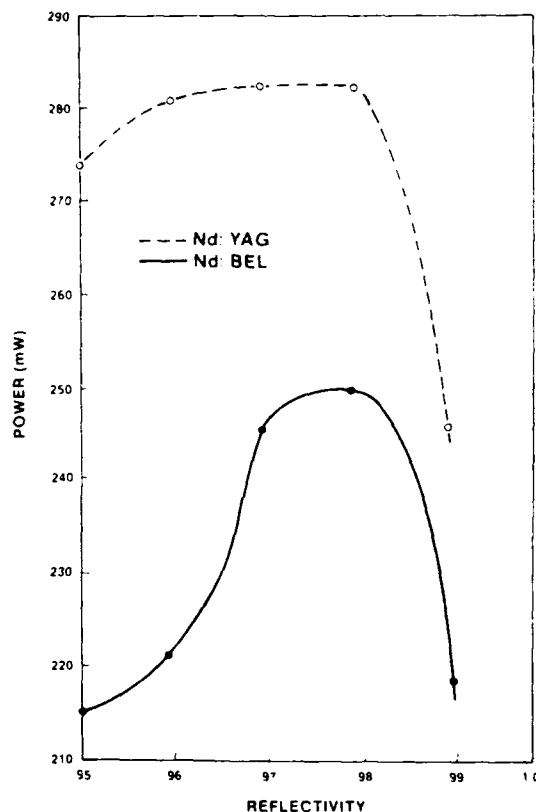

Figure 4. Laser power dependence on output coupling.

As far as improving the overall efficiency of either host, the two lowest factors in Table 2 are the diode efficiency and transfer efficiency. The former can be approximately doubled with presently available devices, and the collection efficiency can be increased to perhaps as high as 90% with well coated and corrected optics. These two improvements alone would produce an overall efficiency of almost 12%.

5. ACKNOWLEDGEMENTS

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3. L. DeShazer, private communication.

4. T. Baer J. Opt. Soc. Am. B, $\underline{3}$, 1175 (1986).